DESIGN AND FABRICATION OF COAXIAL MICRO HELICOPTER

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE

BACHELOR OF TECHNOLOGY

IN

MECHANICAL ENGINEERING

By:

PRATIK MISHRA 108ME002

Under The Guidance of

Prof. J. Srinivas

DEPARTMENT OF MECHANICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA-769008

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CERTIFICATE

This is to certify that the thesis entitled "**Design and fabrication of coaxial micro helicopter**"submitted by **Pratik Mishra (108ME002**) in the partial fulfillment of therequirements for the award of Bachelor of Technology degree in Mechanical Engineering at National Institute of Technology Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance. To best of my knowledge, the matter embodied in this thesis has not been submitted to any other University/Institute for the award of Degree or Diploma

Date:

ProfJ.Srinivas

ACKNOWLEDGEMENT

I wish to express deep sense of gratitude and indebtedness to **Prof. J.Srinivas,** Department of Mechanical Engineering, N.I.T Rourkela, for introducing the present topic and for his constant guidance, constructive criticism and valuable suggestion throughout this project work. I also sincerely thank our senior M.tech students, in charge of CAD LAB, for their kind help and support in my project work.

Place:

Date:

Pratik Mishra (108ME002)

Department of Mechanical Engineering

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Rourkela - 769008

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List of symbols

T_m= Number of teeth on the main gear

T_p = Number of teeth on the pinion gear

G = Gear ratio

N_n = Nominal speed of the main motors

N_a = Actual speed of the motors

V = Voltage of the Li ion battery

KV = KV rating of the main motors

η= Loss coefficient of the motor owing to frictional forces

Ω = Rotational speed of the rotor

W = Weight force on the helicopter body

M_b = Mass of 1 rotor blade

F_L = Lift force on the rotor blade

C_L = Coefficient of lift

Ω_h = Rotational speed of rotor at hover condition

v_b = Linear speed of the blade

A = Area of rotor disk

$F_{L(t)}$= Total lift force acting on the helicopter

$F_{L(b1)}$ = Lift force acting on 1 blade

F_D = Drag force

C_D = Coefficient of drag

F_C = Centripetal force

R = Radius of rotor disk

$\dot{u}$ =Acceleration in x direction

$\dot{v}$ = Acceleration in y direction

$\dot{w}$ =Acceleration in z direction

I =Body inertia tensor

$\boldsymbol{f}$ =Total external force on helicopter

$\boldsymbol{m}$= Moment vector acting on helicopter body

m = Mass of the helicopter body

p =Angular velocity in x direction

q = Angular velocity in y direction

r =Angular velocity in z direction

u =Velocity in x direction

v = Velocity in y direction

w = Velocity in z direction

T =Magnitude of thrust

Q =Magnitude of torque

c_T=Thrust coefficient

c_Q =Torque coefficient

k_T=Thrust constant

k_Q =Torque constant

$\mathbf{t_u}$=Thrust on upper rotor

$\mathbf{t_d}$=Thrust on lower rotor

$\mathbf{q_u}$ =Rotor drag torque on upper rotor

$\mathbf{q_d}$ =Rotor drag torque on lower rotor

$\mathbf{r_{Cu}}$ =Distance of center of gravity from upper rotor axis

$\mathbf{r_{Cd}}$ =Distance of center of gravity from lower rotor axis

$\mathbf{q_{gyro,u}}$ =Gyroscopic torque on upper rotor

$\mathbf{q_{gyro,d}}$ =Gyroscopic torque on lower rotor

$\mathbf{n_T}$=Thrust vector direction

$\mathbf{n_Q}$=Torque vector direction

J_{drive}=Moment of Inertia of the rotor blades about the rotor axis

$\mathbf{g}$ = Gravity vector

ABSTRACT

In this thesis the design of a coaxial micro helicopter is presented and based on the design, a model is fabricated. The thesis starts with the introduction on the previous models of micro helicopters like the Coax and the Epson. The different configurations of the micro helicopters in use are discussed and a detailed introduction on the principle of working of the coaxial configuration of helicopters is presented using the principle of conservation of angular momentum. The advantages and disadvantages of the coaxial configuration over other configurations are then given. The design process starts with the identification of the individual mechanical and electrical parts. The working of the mechanical and electrical components is individually discussed and their necessity for the fabrication process is explained. Further, the mechanical parts are designed and assembled using CATIA V5R17. Then, the model of the coaxial helicopter is fabricated and is successfully flown by remote control mechanism. The individual forces acting on the rotor blades of the fabricated model are identified and their directions are defined. By using standard equations, the values of the individual forces are calculated for the rotor blades as well as for the entire helicopter body.Using the values of the forces obtained on the rotor blades, a static analysis is presented using ANSYS.

Finally, the conclusions and inferences arising in course of the work are presented and the references used in this work are mentioned.

1. INTRODUCTION

In recent times, Unmanned Aerial Vehicles (UAVs) and Micro Aerial Vehicles (MAVs) have been researched upon quite a lot. In particular rotary-winged vehicles are expected to carry out tasks such as monitoring from fixed points that is not expected of a non-rotary winged vehicle. Their ability to hover and carry payload is what makes rotary winged MAVs better as well challenging to control. The vertical landing and take-off is also a feature that only rotary winged MAVs can provide.

Unmanned helicopters are generally better than manned helicopters in terms of safety and cost of production. Micro helicopters are suitable for indoor navigation which cannot be derived from any other aerial vehicle. Many vehicles such as these have been developed like the muFly, the Coax, the MICOR, and the Epson.

The most difficult problem in fabricating a micro helicopter is its control mechanism. The control of a normal size RC helicopter is in itself very difficult. A micro helicopter further involves faster dynamics which makes it even more difficult to control.

In general, the possible fields of use that micro helicopters can be put to use are search and rescue in collapsed structures, exploration in mines and cave structures, defense and surveillance of airports, train stations yet to be constructed, etc.

The aim of this project is to design and fabricate a coaxial micro helicopter that can be put to use in indoor environments. It can be used for surveillance and spying operations.

1.1 Configurations

An important decision to be made for designing a micro helicopter is to select its rotor configuration type. According to theory, many types of configurations are available like the quadrotor, tandem, single rotor and coaxial configurations. But, the mass, size and use constraints limit the rotor configuration type.

In a situation where size is a constraint such as in the situation of fabricating a micro helicopter that requires the wingspan to be minimum and the mass being a constraint as well, a coaxial configuration is the best fit, as it provides the highest lift force or thrust for a given constrained mass and size. In a coaxial set up, due to the higher inflow velocity effected by the upper rotor, the efficiency of the lower rotor reduces to some extent. But despite that the thrust provided in coaxial set up is more than that provided by any other conventional set up**[1]**. More thrust provides for the higher payload carrying capacity that is an asset of the coaxial configuration.

In general, small helicopters with weights from 1 to 50 kg use the single-rotor mechanism, while miniature helicopters with weights less than 500 g use the coaxial-rotor mechanism**[6]**. The tandem configuration is used for military purposes as it has an extreme high payload capacity as there are 2 rotors and there is better balance as well because of the positioning of the rotors.

1.2 Coaxial configuration

Coaxial rotors are a pair of helicopter rotors mounted one above the other on concentric shafts, with the same axis of rotation, but that turn in opposite directions (contra-rotation).The coaxial configuration of helicopters is basically a 2 winged MAV.One of the problems with single rotor blades is the tendency of the helicopter fuselage to spin in the direction opposite to that of the rotors once in flight. This is due to the principle of conservation of angular momentum. The engine or power supply of the helicopter, by exerting torque on the rotor blades, gives substantial angular momentum to the blades. In the absence of external forces such as ground contact, the angular momentum of the blades must be accompanied by a change in angular momentum of the fuselage for momentum to remain conserved. When the power supply rotates the blades, the blades apply equal but opposite torque to the fuselage, causing the fuselage to gain angular momentum in the opposite direction. This phenomenon will cause an imbalance of the system if not checked. To counteract this imbalance, the tail rotor was introduced to keep giving a fixed input of angular momentum to the helicopter body in the direction opposite to that from the main rotor. Thus, the tail rotor acts as a counterbalance. Then, the helicopter's body remains balanced and stable level flight can be achieved. Controlling the torque input by the tail rotor on the body of the helicopter (hence changing the angular momentum input) helps in controlled yaw movement. This demonstrates the extreme maneuverability of the helicopter. The helicopter can even hover and pivot about the rotor axis. Rotational motion in designs that exclude the tail rotors is achieved by using two sets of rotor blades rotating in opposite directions, canceling each other's angular momentum. Coaxial rotors solve the problem arising out of imbalance of angular momentum by turning the rotors in opposite directions to each other. The equal and opposite torques from the rotors that act on the helicopter body, cancel each other out. Yaw control is accomplished by increasing the rotational speed ofone rotor and decreasing that of the other. Thus, there arises a controlled dissymmetry of torque.

1.3 Advantages of coaxial configuration

Dissymmetry of lift is an aerodynamic phenomenon caused by the rotation of a helicopter's rotors during its forward flight. We know that the rotor blades provide lift proportional to the volume of air flowing over their surface. From the top view of a helicopter’s forward flight, we see the rotor disk having 2 rotor blades. The rotor blades move along withthe direction of flight for half of the rotation (advance), and then move in the opposite direction for the next half of the rotation (retreat). During the advance, a rotor blade produces more lift. As a blade moves along with the direction of flight, the forward motion of the aircraft increases the relative speed of the air flowing around the blade with respect to the blade, until it reaches a maximum. At the same time, the other rotor blade in the retreat produces comparatively less lift. As the rotor blade moves away from the direction of flight, the relative speed of the airflow over the rotor blade, with respect to the rotor blade, is decreased by an amount equal to the forward speed of the aircraft, until it reaches its minimum. But, in case of coaxial rotors, the rotors reduce the effects of dissymmetry of lift because they are 2 rotors operating in opposite directions. Hence, when 1 of the rotor blades is in retreat, a rotor blade of the other rotor blade will be in advance. Thus, we can get a more or less constant lift.

The other benefit of coaxial configuration is that it offers more thrust and lift than any other configuration as there are 2 rotors giving lift and there is the absence, in most cases, except in cases of balancing, of a tail rotor that also consumes some part of the engine's power that can now be used exclusively for the 2 coaxial rotors.

But the most important advantage of the coaxial rotor system is that it is an extremely compact structure that can be used for MAVs. It occupies a very small footprint on the ground and is the best option when size and mass are constraints.

The only major disadvantage of the coaxial system is the increased mechanical difficulty which is overshadowed by the advantages of the configuration.

1.4 Rotor system

The rotor system is the rotating part of a helicopter that is responsible for generating lift. A rotor system may be mounted horizontally as main rotors, in which case they provide lift vertically, or it may be vertically mounted, such as a tail rotor, in which case it provides horizontal thrust to counterbalance torque. The rotor mainly consists of a mast, hub and rotor blades.

The mast is a cylindrical shaft generally made of metal that looks like the spine of the system. At the top of the mast is the place where the rotors are attached, which is called the hub.

In the case of the coaxial system, there are 2 masts or shafts that are coaxially mounted without any physical contact between them both. They have a very small clearance distance. Both are respectively mounted on their gear systems that connect them to the transmission, which is a battery in case of micro helicopters. The rotors are hinged to the respective shafts at the hub.

Most helicopters have a single main rotor, but torque created as the engine turns the rotor against its air drag causes the body of the helicopter to turn in the direction opposite to the rotor. Hence to counter this effect, some sort of anti-torque mechanism must be used. Thus the tail rotor design is introduced to balance the torque effect by pushing or pulling against the tail.

1.5 Literature review

Bermes et al.**[1]** presented the design of two prototypes of the autonomous micro helicopter muFly, which were built and flown in untethered test flights. The rotor configurations and steering principle selection are discussed and selection of coaxial configuration with swashplate steering mechanism is justified on the basis of dynamic simulation results. The two designs are compared and their system integration issues are solved.

Schafroth et al. **[2]**presented the design process of robust H_∞-control for a coaxial micro helicopter by developing a nonlinear dynamic model taking into account all the essential elements of the helicopter. The system parameters are identified using measurement data from test benches and CMA-ES (Covariance Matrix Adaptation Evolution Strategy). The verified model is used for design process of H_∞-controllers for attitude and heave control, which are tested in real flight.

Sheng et al. **[3]**designed an autonomous takeoff and landing control strategy and implemented it for a prototype coaxial unmanned helicopter with ducted fan configuration. The control strategy is designed such that longitudinal and lateral controls use ground forces, attitude and drifting feedbacks. Ground forces feedback is used to balance longitudinal forces and moments during liftoff effectively cancelling all ground forces. Attitude and drifting feedbacks are used to balance the longitudinal and lateral movements of the helicopter during takeoff and landing. The flight control strategy is successfully verified during flight tests.

Bramwell et al. **[4]**derived thoroughly the various equations governing the motion of the rotor blades and the various stresses acting on different parts of the blade as well as on the individual components of the helicopter.

Limnaios and Tsourveloudis **[5]**presented the design process of a fuzzy logic based controller for a coaxial micro helicopter and tested the developed controller for altitude, attitude, and position control through simulations on an identified non-linear model of the helicopter.The robustness properties of the controller to parameter variations of the model is assessed, as well as, its ability to accommodate or absorb external disturbances.

Nonami et al.**[6]**presented the modeling and control system design of unmanned helicopters by obtaining their mathematical model as a transfer function or state space equation and subsequently, using the optimal control design for the control method for both small and miniature unmanned helicopters.

Heyong and Zhengyin **[7]**solved the three-dimensional unsteady Euler equations numerically to simulate the unsteady flows around forward flight helicopter with coaxial rotors based on unstructured dynamic overset grids and found that the performance of both the coaxial rotors becomes worse because of the aerodynamic interaction between them, and the influence of the top rotor on the bottom rotor is greater than that of the bottom rotor on the top rotor. The downwash velocity at the bottom rotor plane is much larger than that at the top rotor plane, and the downwash velocity at the top rotor plane is a little larger than that at an individual rotor plane. The downwash velocity and thrust coefficient both become larger when the collective angle of blades is added. When the spacing between the two coaxial rotors increases, the thrust coefficient of the top rotor increases, but the total thrust coefficient reduces a little, because the decrease of the bottom rotor thrust coefficient is larger than the increase of the top rotor thrust coefficient.

Schafroth et al. **[8]**investigated the aerodynamics and flight dynamics experimentally to gather information for the design of the helicopter’s propulsion group and steering system. Several test benches are designed and built for these investigations. A coaxial rotor test bench is used to measure the thrust and drag torque of different rotor blade designs. The effects of cyclic pitching of the swash plate and the passive stabilizer bar are studied on a test bench measuring rotor forces and moments with a 6–axis force sensor. The gathered knowledge is used to design a first prototype of the muFly helicopter.

Koehl et al. **[9]**presented a comprehensive design of a Gun Launched Micro Air Vehicle (GLMAV). The MAV packaged in a projectile is launched using the energy delivered by a portable weapon. A detailed GLMAV nonlinear mathematical model is presented for hover and near-hover flight conditions and identified from experimental load data using a strain-gage aerodynamic balance. The parameter estimation is based on the Kalman filter estimation method applied to the simplified aerodynamic model and using the input-output data from the experiment. The persistently exciting condition is given in terms of physical variables of the GLMAV through two simple expressions. The identification results are presented and validated through comparisons between the model output and real load data.

Chen et al.**[10]**discussed two papers dedicated to design of unconventional and micro UAVs..This editorial page also puts forward three papers on UAV stabilization, autonomous flight, and intelligence control. In addition, this special issue gathers two papers on road and terrain following and finally, there are three papers discussed focusing on path planning.

Cai et al.**[11]**presented a comprehensive design methodology for constructing small-scale UAV helicopters and explain the systematic design procedure, which includes hardware component selection and design to construct a fully functional UAV helicopter, named SheLion.

2. DESIGN AND FABRICATION

The design of the coaxial micro helicopter is carried out with a thorough understanding of the working of the various mechanical elements and parts used in the fabrication of the coaxial system. The various mechanical elements of the system are:

- Outer shaft
- Inner shaft
- Stabilizer bar
- Upper rotor blade
- Lower rotor blade
- Gear arrangement
- Tail rotor blade

The electrical components are of equally vital significance in the fabrication the helicopter. The different electrical components used during the course of fabrication are as follows:

- Power supply (Li ion Battery)
- Micro controller
- Electric motors

The course of action for this chapter included a detailed design of the individual mechanical components of the helicopter and then fabricating by assembling all the mechanical and electrical components at the required places.

2.1 Fabrication

For fabrication, a toy helicopter manufactured by ZG COPTER is taken as the starting model. Some parts of the starting model are disassembled and are incorporated in the final model of the helicopter. Firstly, a base is created of balsa wood to mount the fuselage. The landing pad is then constructed by cutting of a measured portion of packaging thermocol. The strip of thermocol is then glued to the bottom side of the balsa plate using fevikwik glue. The rotor system of the starting model is then disassembled and is mounted on the balsa plate by using fevikwik glue. The main motors of KV rating 1600 are then mounted in the space where the motors of the starting model were previously mounted. The tail motor and tail rotor are then disassembled and are connected to the programmed microprocessor that is obtained from the working model. This microprocessor is programmed according to the remote control transmitter body of the starting model, which is also used in the final model. The Li ion battery of 3.7V 150mAh specification is then connected to the microprocessor. For the charging requirements of the batteries of the transmitter, a NOKIA charger's charging end is cut off and is connected to the charging wire of the transmitter by solder. The points where wires are connected are then wound with cello tape to avoid the open points to short circuit. The helicopter is then successfully flown by controlling it with the transmitter box. The final model is shown in Fig.2.1.

Fig.2.1 Fabricated final model of coaxial micro helicopter.

2.2 Outer shaft

The outer shaft is connected mechanically to the lower rotor by a hinge at the hub. The rotor blades are bolted to the hub. The outer shaft has a diameter of 2.5 cm. The upper part of the shaft is connected to the hub that holds the lower rotor blades while the lower end of the shaft is mounted on the bigger gear of the upper gear system as shown in Fig.2.2. The outer shaft is made up of fiber and it rotates freely with the gear on which it is mounted.

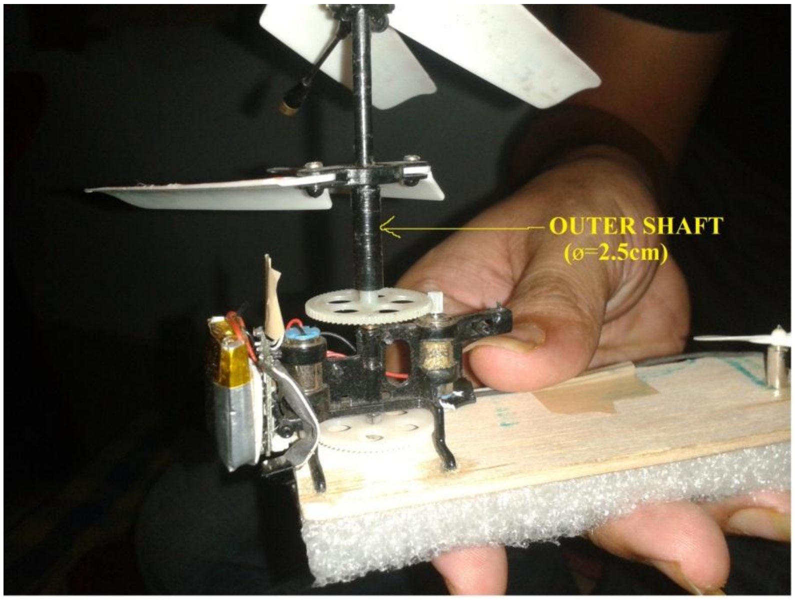

Fig.2.2 Outer shaft of the model helicopter of diameter 2.5cm.

2.3 Inner shaft

The inner shaft lies coaxially within the outer shaft without any mechanical contact between the two shafts. The upper end of the inner shaft is connected with the hub which holds the blades of the upper rotor by means of bolts. The additional task that the inner shaft performs is that it provides carries a hub that holds the stabilizer bar, which provides necessary stability to the coaxial system. The stabilizer bar is linked to the hub of the upper rotor by a ball and rod joint shown in Fig.2.3. The linkages involved in the inner shaft are shown in Fig.2.4. The diameter of the inner shaft is 1.5cm. The lower end of the inner shaft is mounted on the larger gear of the lower gear arrangement.

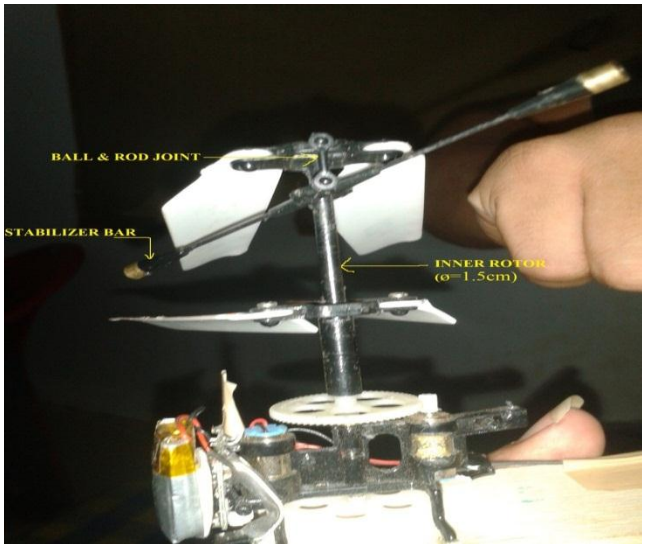

Fig.2.3 Inner rotor of diameter 1.5cm along with stabilizer bar and ball and rod joint.

2.4 Stabilizer bar

The stabilizer bar gives cyclic pitch input to the upper rotor and stabilizes the helicopter in flight. The stabilizer bar is linked with the upper rotor by a ball and rod joint as shown in Fig.2.3. The upper rotor, the stabilizer bar and the ball and rod joint is considered to be a single system. In comparison to the other parts of the helicopter, the stabilizer bar system is a massive object, i.e. it has a high mass. Due to the resulting high inertia, this system lags behind a pitch or roll movement of the helicopter body as shown in Fig.2.4. Thus there is a time delay for the upper rotor and stabilizer bar to react to the movement and due to its high inertia, it exerts a redress moment on the total system in the opposite direction of the roll/pitch movement. This redress moment balances the helicopter in flight. The stabilizer bar used is a 9 cm long 2x stabilizer balance bar, which is shown in Fig.2.5.

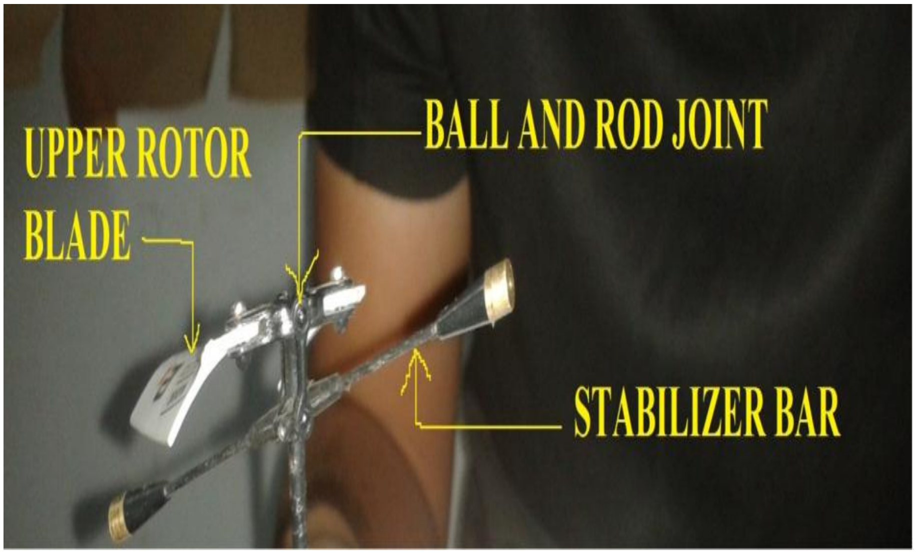

Fig.2.4 Stabilizer bar system

Fig.2.5 A 2x stabilizer balance bar with the ball and rod joints separated from it.

2.5 Upper rotor blade

The upper rotor blade used is taken from an already existent toy helicopter. The blade profile is designed in CATIA after taking the measurements of the different physical dimensions. It is made of polystyrene. The blade profile specifications are as follows:

Longitudinal length from hinge to free end: 6 cm.

Blade width at free end: 1.4 cm.

Blade width at hinged end: 1.9 cm.

The thickness of the blade is very small.

The isometric view of the upper blade design is shown in Fig.2.6.

2.6 Lower rotor blade

The lower rotor blade used is also detached from a previously existent toy helicopter. The dimensions of the lower rotor blade are the same as that of the upper rotor blade. It is made of polystyrene.

The angle of bend of the rotor blades is measured approximately using a ruler box protractor and is found to be 22 degrees. The mass of the rotor blades is found to be 0.42 g. The mass of the blade is measured in an air tight weighing machine in the tribology laboratory of NIT Rourkela. The blade profile of the lower blade is also shown in the CATIA screenshot in Fig.2.5 and Fig.2.7.

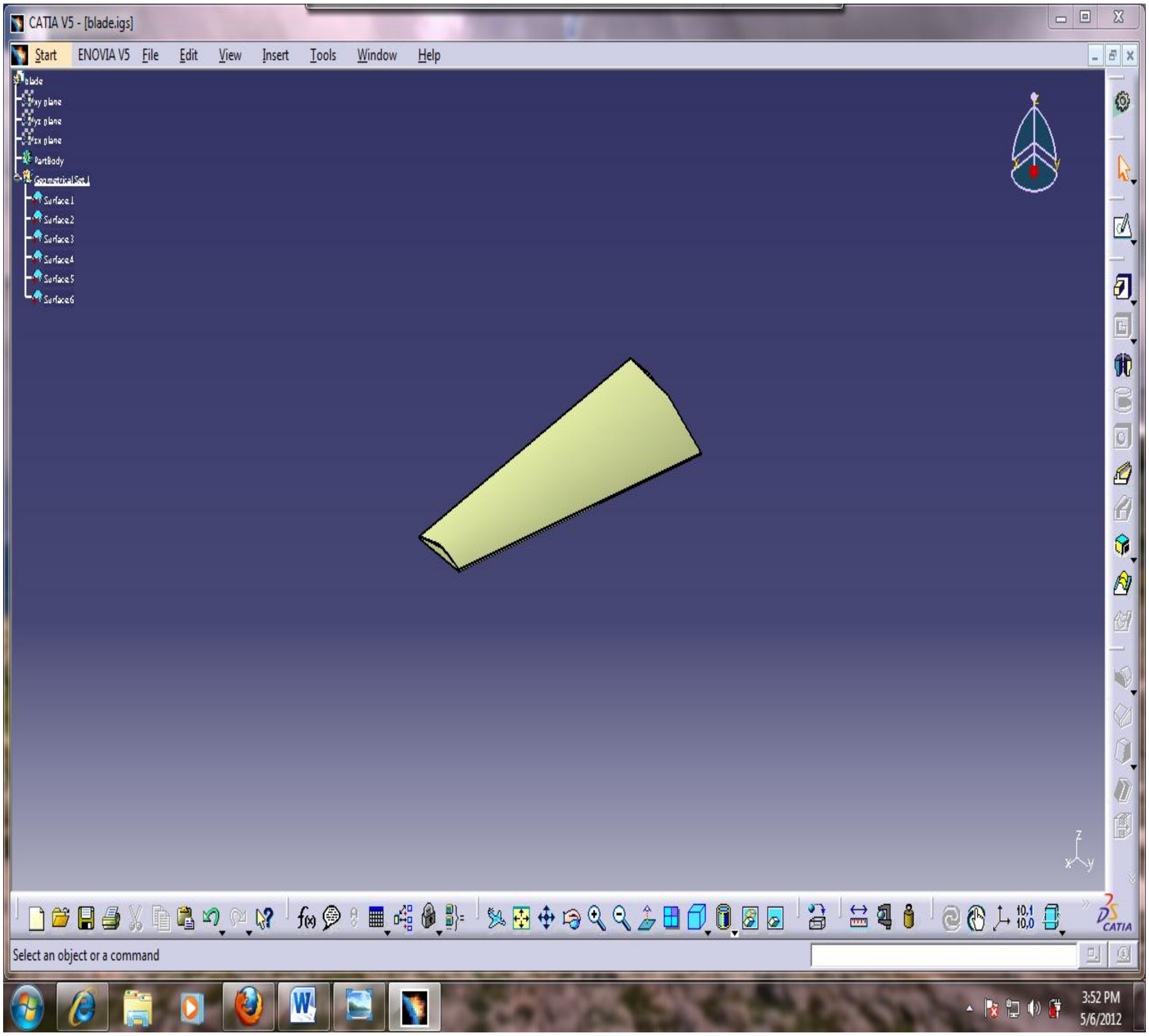

Fig.2.6 A screenshot of the isometric view of CATIA design of rotor blade

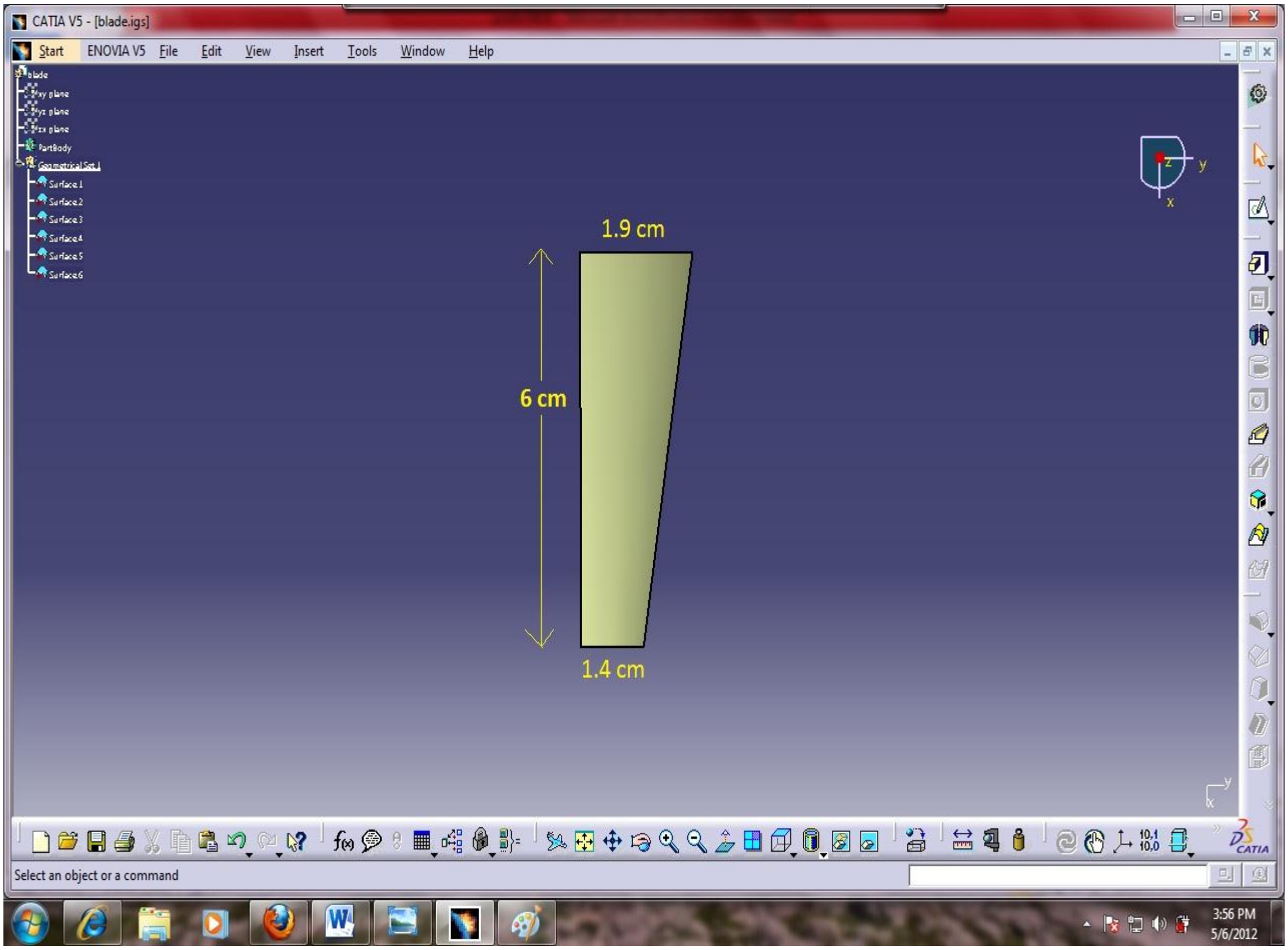

Fig.2.7 Top viewof the upper as well as the lower rotor blade along with the dimensions.

2.7 Gear arrangement

There are 2 simple sets of gears used in the model for reduction of speed of the shafts in comparison to the motors. The motors rotate at very high speeds and it is very difficult for the rotor blades as well as the shaft to withstand the extreme stresses developed at speeds of 5920 rpm developed in the motor. The pinion gear is mounted on the motor shaft and rotates with the same speed as that of the motor. The motor in the model develops a speed of approximately 6000 rpm. The main gear is mounted on either the inner or shaft of the helicopter that holds the hub that carries the blades. The main and pinion gears are meshed and therefore we get a speed reduction for the shafts. The specifications for the gears are:

Number of teeth of main gear (T_m) : 70

Number of teeth of pinion gear (T_p) : 7

Gear ratio (G) : 10

The lower gear set shown in Fig.2.8 is attached to the inner shaft and the upper gear set is attached to the outer shaft.

2.8 Tail rotor blade

The tail rotor blade is a small fan like structure that is used for the balance of the helicopter body while lifting up as shown in Fig.2.9. The body of the helicopter becomes imbalanced as the motor and the rotor blades are set at the front of the helicopter body. Thus the lift force produced acts at the front end of the body and the back end has only its gravity pushing down. Here the tail rotor provides a small lift for the less massive tail end to lift up along with the more massive front end.

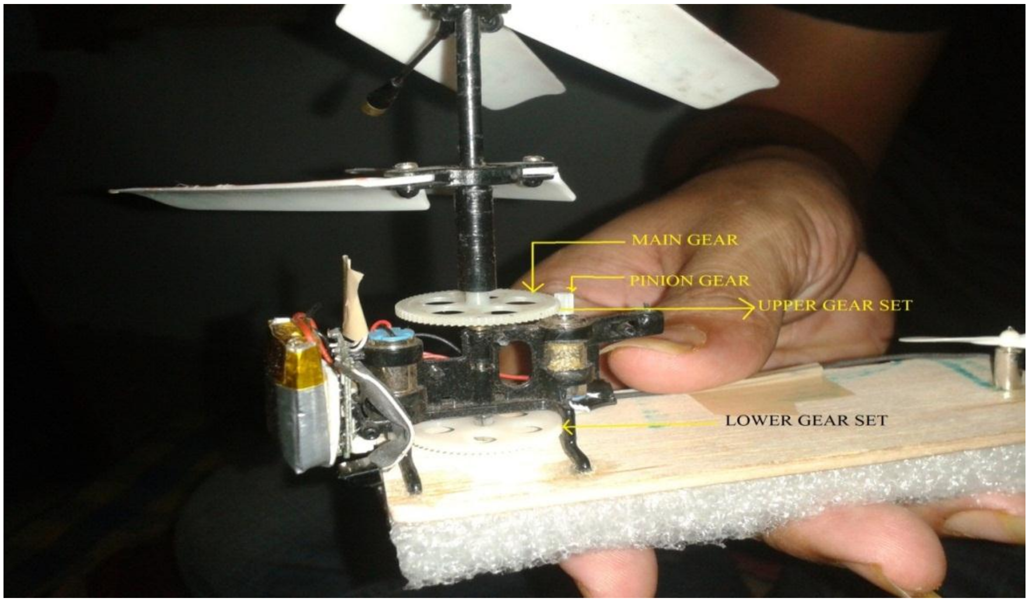

Fig.2.8 Gear arrangement showing the main and pinion gears of the model

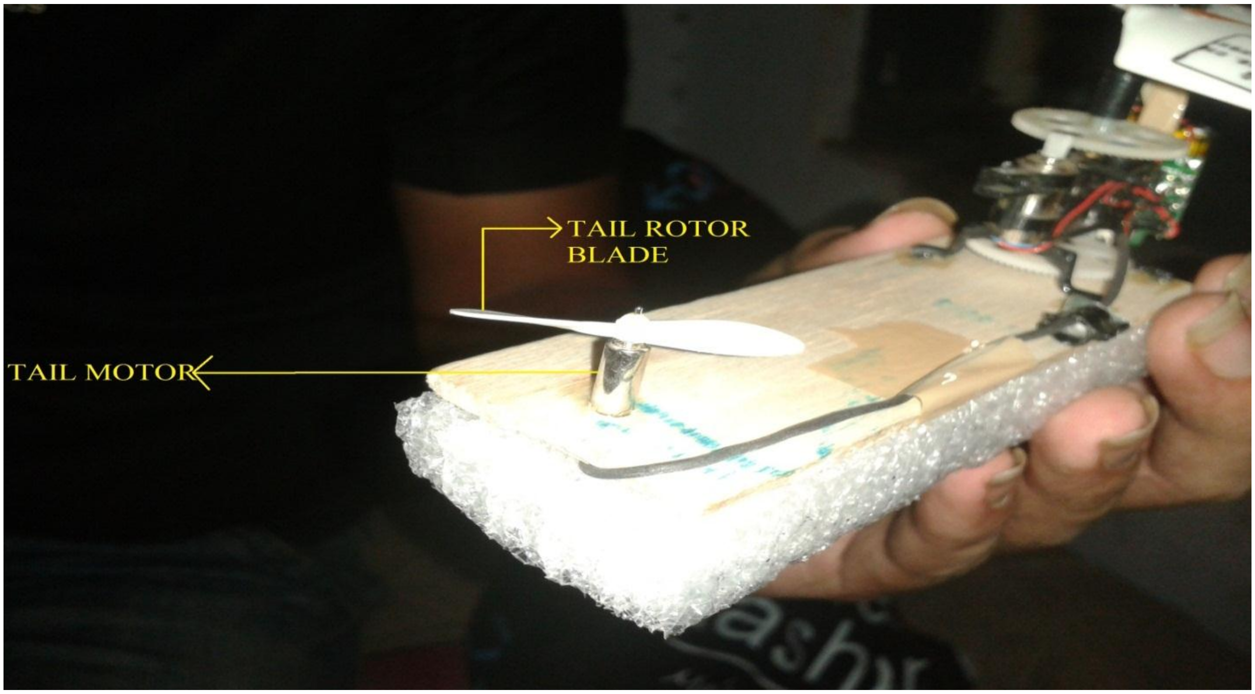

Fig.2.9 Tail motor and tail rotor blade

2.9 Power supply

The power is supplied for the model from a 3.7 V 150mAh Li ion battery. This battery is very useful as it provides a high power with a small size, which is shown in Fig.2.10. Due to its small size it perfectly fits into the requirements of a micro helicopter. The battery is rechargeable up to 1000 times. The battery is directly connected to a microcontroller and it gives power to the system through the programmed microcontroller. The specifications of the battery are:

Weight	:	3.0 g
Dimensions	:	4mm×17mm×19mm
Nominal voltage	:	3.7 V
Charging voltage	:	4.2 V
Typical capacity	:	150 mAh

Fig.2.10A 3.7 V 150 mAh Li ion battery used in the model

2.10 Micro controller

A micro controller already programmed and used in a toy helicopter is used for the model. The micro controller processes the inputs that are given to it via the transmitter by the help of an IR receiver or Thin Small Outline Packtime (TSOP). This micro controller is essential for controlling the speeds of the motors. It derives power from the LiPo battery and after processing the signal from the transmitter sends appropriate signals to the main as well as the tail motors.

It has 2 incoming wires(1 red and 1 black), which are negative and positive wires from the battery and it has 6 outgoing wires(3 reds and 3 blacks), 1 red and 1 black each as negative and positive wires for the 3 motors.

2.11 Electric motors

The electric motors used in the model are of 2 types:

2 Main motors.

1 Tail motor.

The two main motors are mounted on a set up as shown in Fig.2.11. The motors have a KV rating of 1600. They act on a voltage of 3.7 V from the LiPo battery, which gives them a nominal speed of

$N_n = V \times KV = 3.7 \times 1600 = 5920$ rpm.

But due to the internal losses due to back EMF of the motor, it is assumed it offers a speed approximately 80% of its nominal value. Hence, actual speed of motor:

$$N_a = \eta \times V \times KV = 0.8 \times 3.7 \times 1600 = 4736 \text{ rpm.}$$

Now, due to the gear system, there is a speed reduction for the shafts and consequently for the rotor blades. Hence, the actual speed of the blades is:

$$\Omega = \eta \times V \times KV/G$$

$$\Omega = 0.8 \times 3.7 \times 1600/10 = 473.6 \text{ rpm.}$$

The motors are brushless DC motors (BLDC), which weigh 3.6 g and are used because of their superior efficiency and more lasting period in comparison to brushed motors.

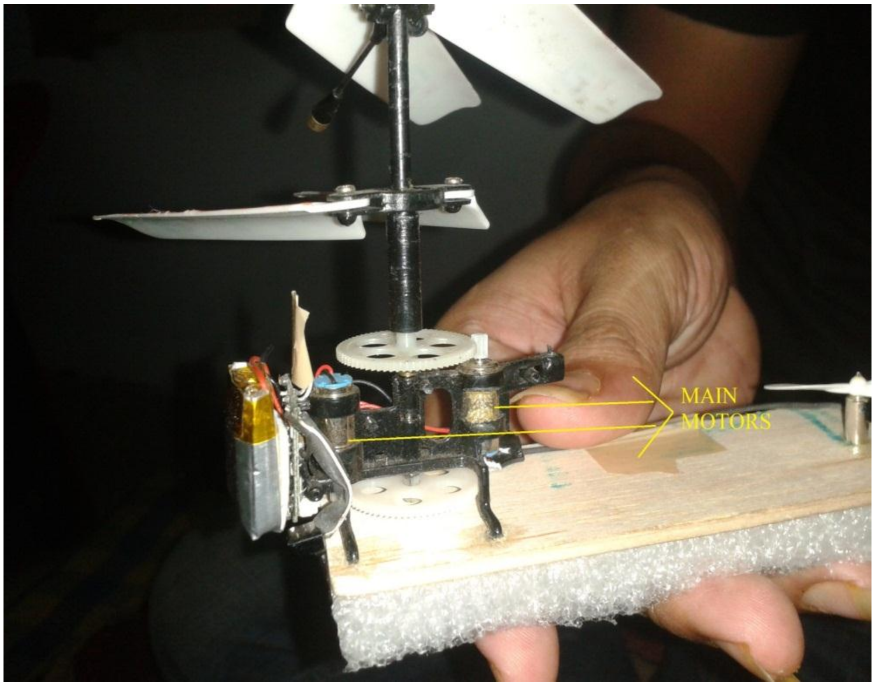

Fig.2.11 Main motors used in the model

2.12 Electronics interface

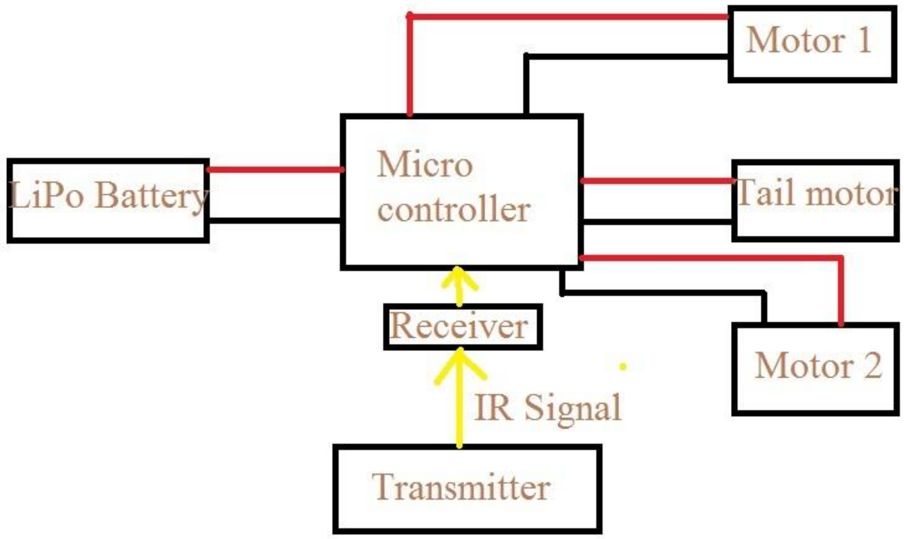

Fig.2.12 Block diagram showing electronics interface and wiring in the model

Fig 2.12 shows a block diagram showing the electronics interface and the wiring of different electronics components of the helicopter. The red lines represent the positive wires and the black lines are the negative wire connections. The yellow arrow from transmitter to receiver represents the infra-red (IR) signal sent from the former to the latter. The receiver is a TSOP that receives the signal and passes it to the micro controller.

The designs of the various parts of the coaxial system are very important before fabrication. Hence detailed designs of the individual parts as well as the final assembly of the helicopter chassis using CATIA is done. Fig.2.13 shows the CATIA modeling.

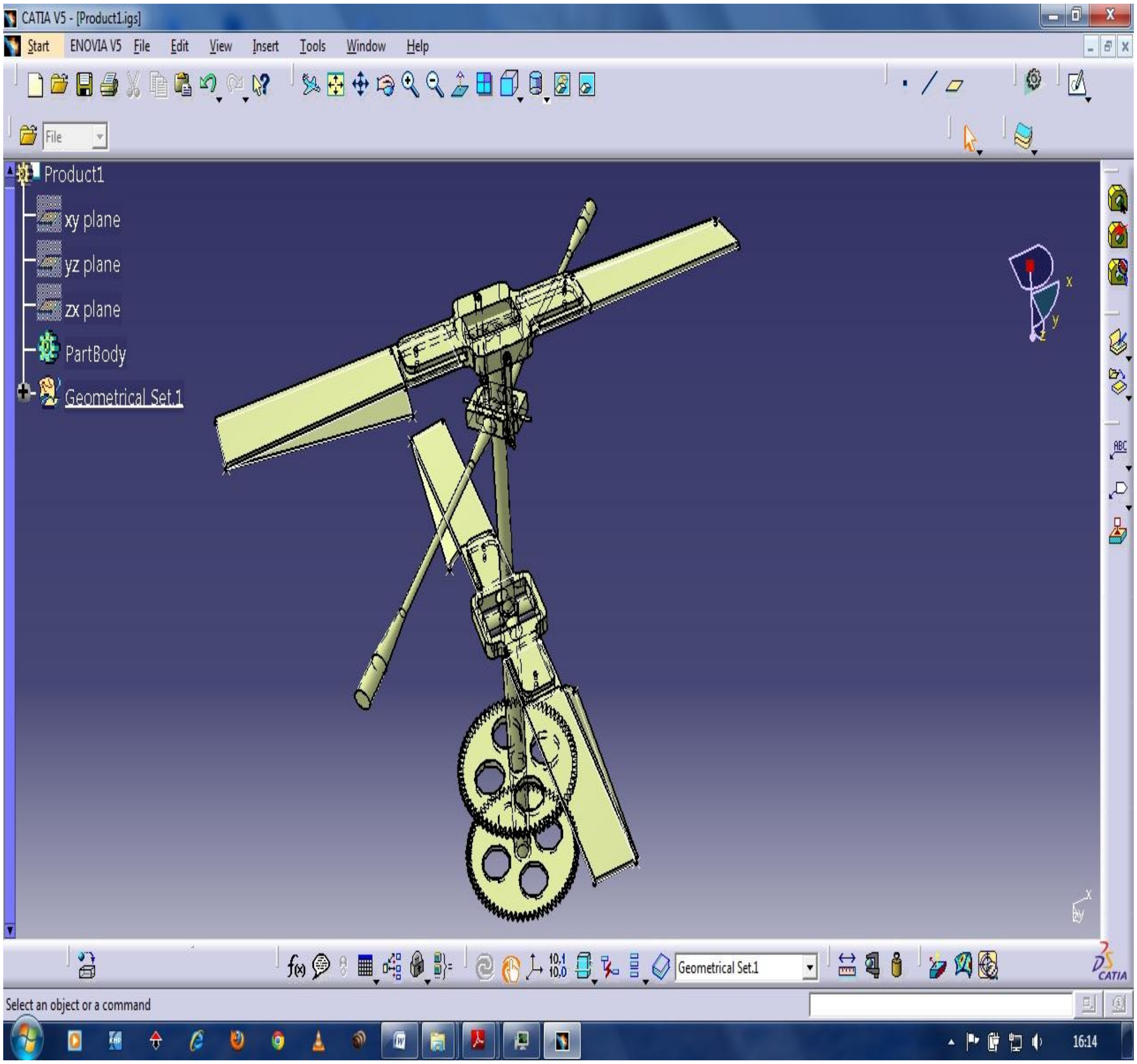

Fig.2.13 A snapshot of the CATIA modeling of the helicopter assembly

3. EQUATIONS OF MOTION

This chapter presentsa nonlinear modeling of the dynamic forces acting on the helicopter fuselage by considering the physics and dynamics of the different components of a coaxial micro helicopter.

3.1 Newton-Euler's equation

As commonly done in aeronautics, an inertial frame J and a body fixed frame B are introduced. This gives the transformation equations for velocity, position, angles and angular rates. Using fundamental Newtonian mechanics, the equations for rigid body motion in the body fixed frame **[2]**, which is located at a helicopter's center of gravity, are:

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \frac{1}{m}\boldsymbol{f} - \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} u \\ v \\ w \end{bmatrix} \tag{3.1}$$

and

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = I^{-1}\left(m - \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times I \begin{bmatrix} p \\ q \\ r \end{bmatrix}\right) \tag{3.2}$$

Thus far, the equations of motion are standard and are independent of flight platform.

Now the total external force ***f***and moment ***m*** vectors are to be defined.

The forces acting on the helicopter are as follows **[2]**

$$\boldsymbol{f} = \mathbf{t_u}+\mathbf{t_d}+\mathbf{g}+\mathbf{w_{drag}} \ , \tag{3.3}$$

$$\boldsymbol{m} = \mathbf{q_u} + \mathbf{q_d} + \mathbf{r_{Cu}} \times \mathbf{t_u} + \mathbf{r_{Cd}} \times \mathbf{t_d} + \mathbf{q_{gyro,d}} + \mathbf{q_{gyro,u}}, \tag{3.4}$$

Now, the single forces and moments are defined both for lower as well as upper blade.

The rotor thrust **[2]** is $\mathbf{t}_i = T_i \, .\mathbf{n}_{Ti}$ (3.5)

And, the rotor torque **[2]** is $\mathbf{q}_i = Q_i \, .\mathbf{n}_{Qi}$ (3.6)

Now, in hover, the thrust and torque magnitude T and Q of a rotor of radius R can be defined as **[4]**

$$T_i = c_{Ti}\pi\rho R^4 \boldsymbol{\Omega}_i^2 = c_{Ti} k_T \boldsymbol{\Omega}_i^2 \tag{3.7}$$

$$Q_i = c_{Qi}\pi\rho R^5 \boldsymbol{\Omega}_i^2 = c_{Qi} k_Q \boldsymbol{\Omega}_i^2, \tag{3.8}$$

Here, $k_T = \rho\pi R^4$ and $k_Q = \pi\rho R^5$.

The thrust vector is described using two tilt angles α and β around the x and y axis as shown in Fig.3.1. The expression for thrust vectors **[2]** using Fig.3.1 are

$$\mathbf{n}_{Ti} = \begin{bmatrix} \cos\alpha \sin\beta \\ \sin\alpha \\ -\cos\alpha\cos\beta \end{bmatrix} \tag{3.9}$$

The rotor torque vectors act only in z axis but it has to be considered that, when seen from above, the lower rotor turns clockwise while the upper rotor turns anticlockwise **[2]**.

The next and last torque is that resulting from acceleration of rotors. It might be negligible for lower rotor, but due to the high inertia of the upper rotor system due to the stabilizer bar, the torque produced is noticeable. Thus, the gyroscopic torque that acts only in the rotor axis direction is

$$Q_{gyro,i} = J_{drive,i}\dot{\Omega}. \tag{3.10}$$

Thus, the dynamic analysis is done by listing the forces and expressing them in terms of variables.

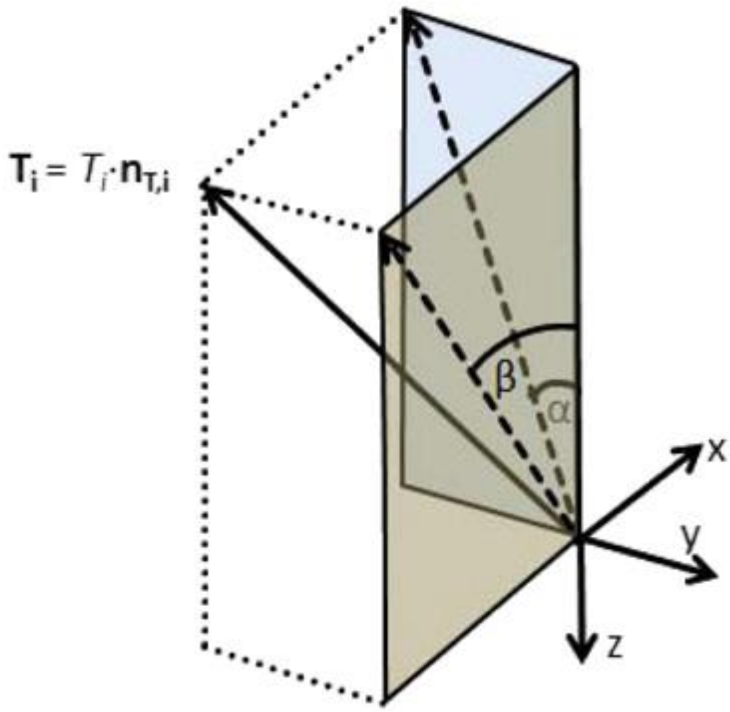

Fig.3.1 Representation of the tilted thrust force with tilting angles α and β [2].

Here, Fig.3.1 shows the representation of the tilted thrust force with tilting angles α and β.

3.2 Micro helicopter control

Control structure for full control of a micro helicopter consists of 6 independent controllers **[5]**.

1.Altitude control

2. Yaw control

3. Pitch and Roll control

The x and y position controllers generate reference inputs to be tracked by pitch and roll controllers.

4. RESULTS AND DISCUSSIONS

4.1 Force calculations

There are a number of forces acting on the rotor blades that are analyzed using ANSYS. First of all the forces are identified. The first force that acts on the rotor blades is its own weight downwards at its center of gravity. The second force is the lift/thrust force that acts on the blades on account of the cutting of airstream by the curvature of the blades. Thirdly, as the blades rotate, they cut the airstream and therefore, the airstream also exerts a force on the blades due to the air resistance. This is the drag force that acts on the blades of the rotor. And finally, on account of the rotation of the rotor blades, there acts a centrifugal force on the blades.

The next step is to consider the forces separately and find out their values for the rotor blades individually.

4.1.1 Weight

Due to the mass of the blades, there acts a weight force downwards at the center of gravity of the blades. An individual blade is considered and the force value is found for it. Now, we know that:

$$W = M_b g \tag{4.1}$$

The mass of an individual blade is measured in the air tight weighing machine in the tribology laboratory of NIT Rourkela and is found to be 0.29 g.

Hence, $W = 0.29\times10^{-3}\times9.8$

$W = .002842$ N.

And, weight of the helicopter body of mass 20.2g is

$W_b = .0202\times9.8 = 0.19796$ N.

4.1.2 Lift/Thrust Force

When the blade cuts across an airstream, there is a flow of air both above and below the blade. The blade profile is such that the air that passes above the blade has to travel more distance in the same time as compared to the air that passes below the blade. Hence, the air that passes above the blade has a higher velocity than the air that passes below it. Now, according to Bernoulli's principle, the fluid having higher velocity is at a lower pressure. Hence, the air above the blade, due to its higher velocity, is at a lower pressure. That means there is a pressure difference between the air above and below the blade. Thus there arises a force from the high pressure region to the low pressure region. This is the lift force that acts essentially in the upward direction due to the blade profile.

The lift force on a blade is given approximately by:

$$F_L = 0.5 \times C_L \times \rho \times v_b^2 \times A \tag{4.2}$$

Now, the area A is the area of the total rotor disk. So, area A is given by:

$$A = \pi R^2 \tag{4.3}$$

Here, R = 6cm. So, area of the rotor disk is:

$$A = 3.14 \times (0.06)^2$$

$$\Rightarrow \quad A = 0.011304 \text{ m}^2$$

Here C_L is assumed to be 1.6, a typical lift coefficient value.

Density of air is taken as 1.29 kg/m^3. So, ρ = 1.29 kg/m^3.

The angular velocity of the blades N_b is already found out in 2.10 to be 473.6 rpm.

The rotational speed Ω of the blades is: Ω = 473.6/60 = 7.894 rev/s

So, the linear velocity of blades in m/s is:

$$v_b = 7.894 \times 2 \times \pi \times 0.06 = 2.974 \text{ m/s.}$$

Hence the lift force comes out to be:

$F_L = 0.5\times C_L\times\rho\times v_b^2\times A$

⇨ $F_L = 0.5\times1.6\times1.29\times2.974^2\times0.011304$ N.

⇨ $F_L = 0.103179$ N.

Now, combining the lift force for the 2 rotor disks, we get the total lift force acting on the helicopter fuselage.

Hence, $F_{L(t)} = 2\times0.103179 = 0.206358$ N.

Now, for purposes of analysis of stresses on the rotor blades, by approximation, lift force on 1 blade is:

$F_{L(b1)} = 0.103179/2 = 0.051589$ N.

The lift generated by the tail rotor is neglected in this analysis as it is considered to be very small in comparison to that generated by the main rotor blades.

4.1.3 Drag Force

The drag force acts on the rotor blades as they cut through the airstream. As they do so, they exert a force on the airstream, which itself exerts a force opposite to the direction of movement of the rotor blades. This force is called the drag force.

Drag force is given by: $F_D = 0.5\times C_D\times\rho\times v_b^2\times A$ (4.4)

Coefficient of drag C_D is assumed to be 0.5 which is a typical value for helicopters.

Hence, drag force comes out to be:

$F_D = 0.5\times0.5\times1.29\times2.974^2\times0.011304$

⇨ $F_D = 0.032243$ N.

4.1.4 Centrifugal Force

As the blade rotates at a very high speed of 473.6 rpm, there is a force acting towards the center of the hub along the plane of the blade. This force is the centrifugal force which is an inherent force for any rotating body.

The centrifugal force is given by:

$$F_C = M_b\Omega^2 R \tag{4.5}$$

⇨ $F_C = 0.29\times10^{-3}\times(473.6/60)^2\times0.06$

⇨ $F_C = 0.001084$ N.

Fig.4.1 shows the various forces acting on the CATIA model of the rotor blade. The weight acts downwards at the center of gravity. The lift force acts at the center of gravity as well but upwards. The drag force acts opposite to the direction of motion of the rotor blade as shown. And finally, the centrifugal force acts away from the hinge as shown.

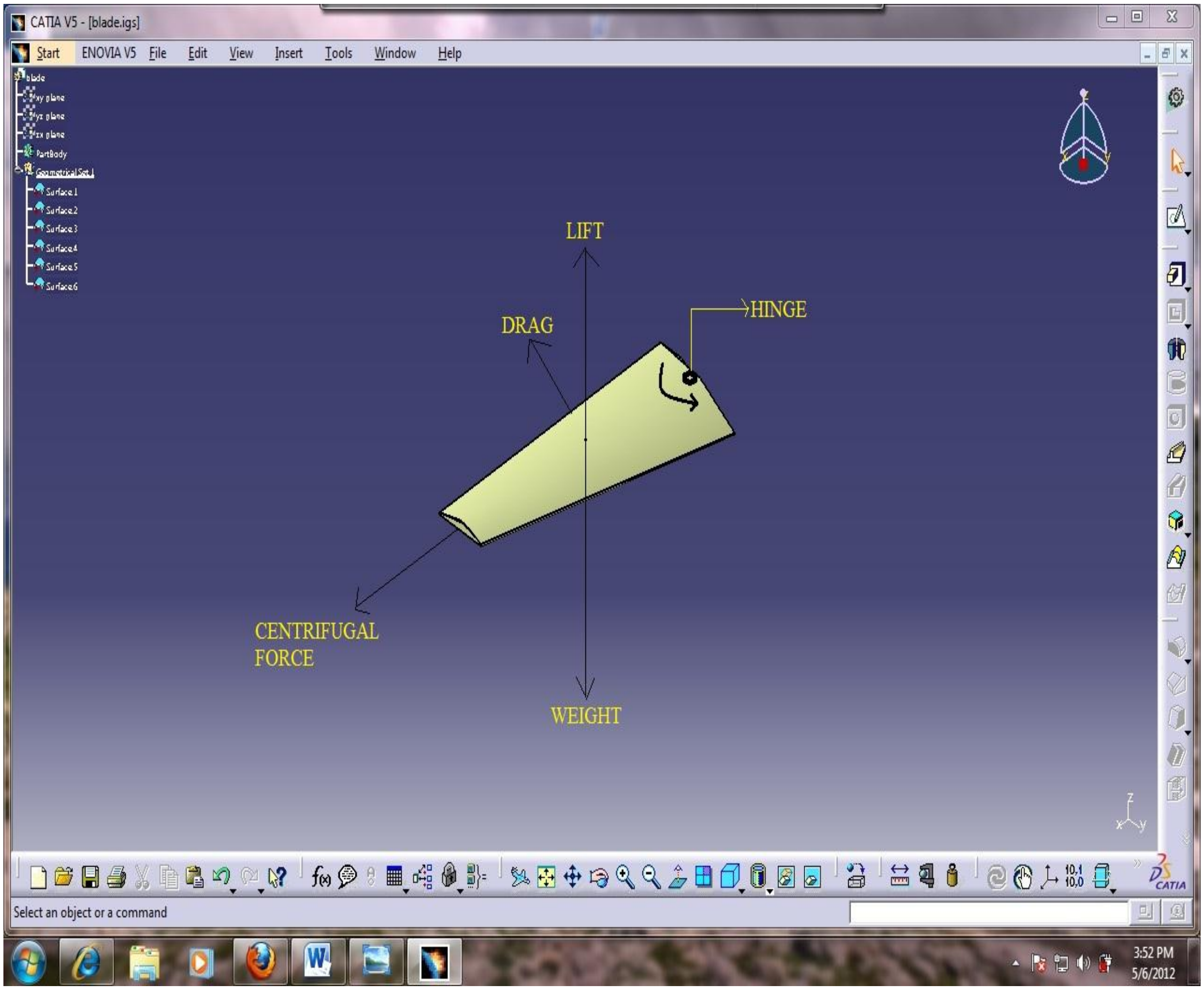

Fig.4.1 Forces acting on the blade shown in a CATIA screenshot

4.2 Finite element analysis

The next step of the analysis is to show the stress and strain acting at different parts of the rotor blade. The software used for this is ANSYS. The material given for the blade is Polystyrene. The properties of the polystyrene material are given in ANSYS and the CATIA model is meshed using Quad (6 node) element type. The properties of polystyrene used are:

Density:	1.05 g/cm^3
Thermal conductivity:	0.036 W/(m·K)
Tensile strength:	52 MPa

Young's modulus: 3300 MPa

Linear expansion coefficient: 8×10^{-5}/K

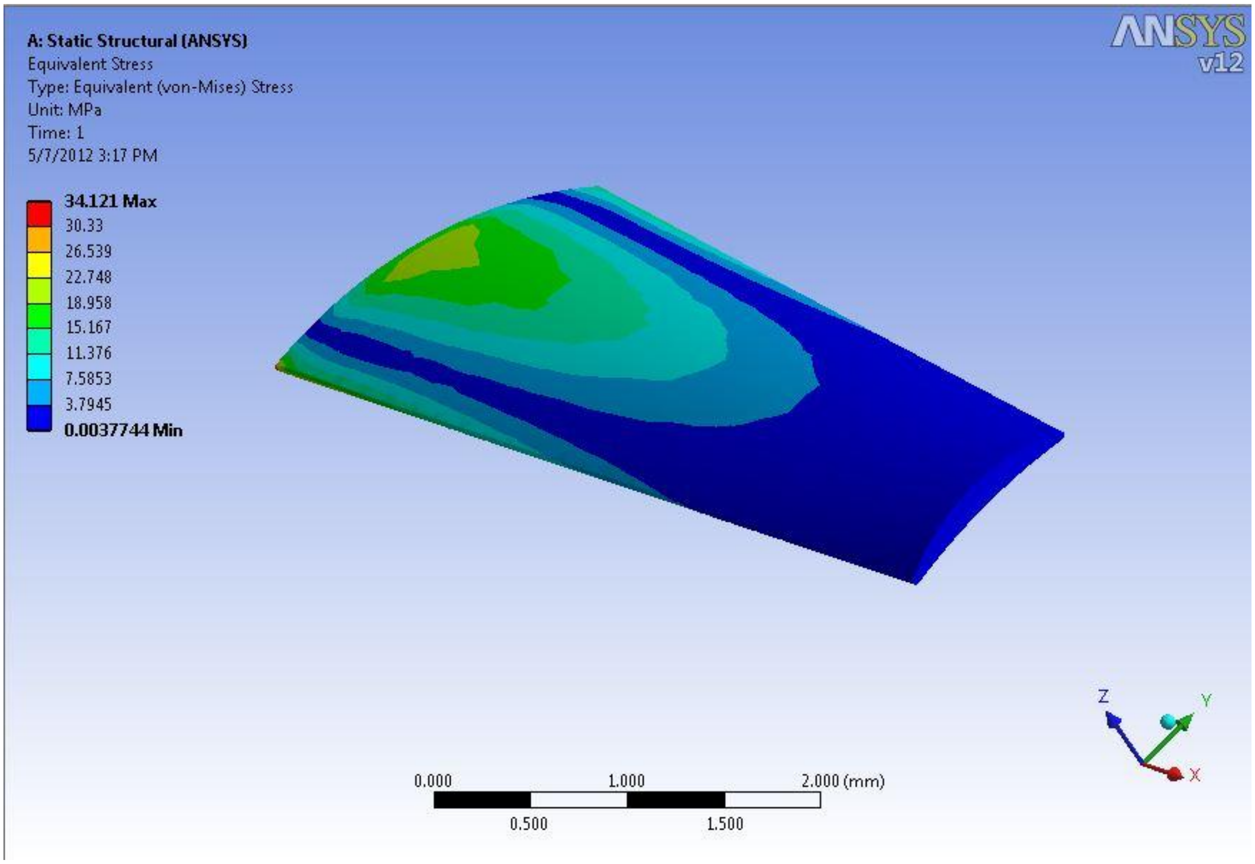

Fig.4.2 A screenshot of the von-Misesequivalentstress analysis of the rotor blade under load in ANSYS

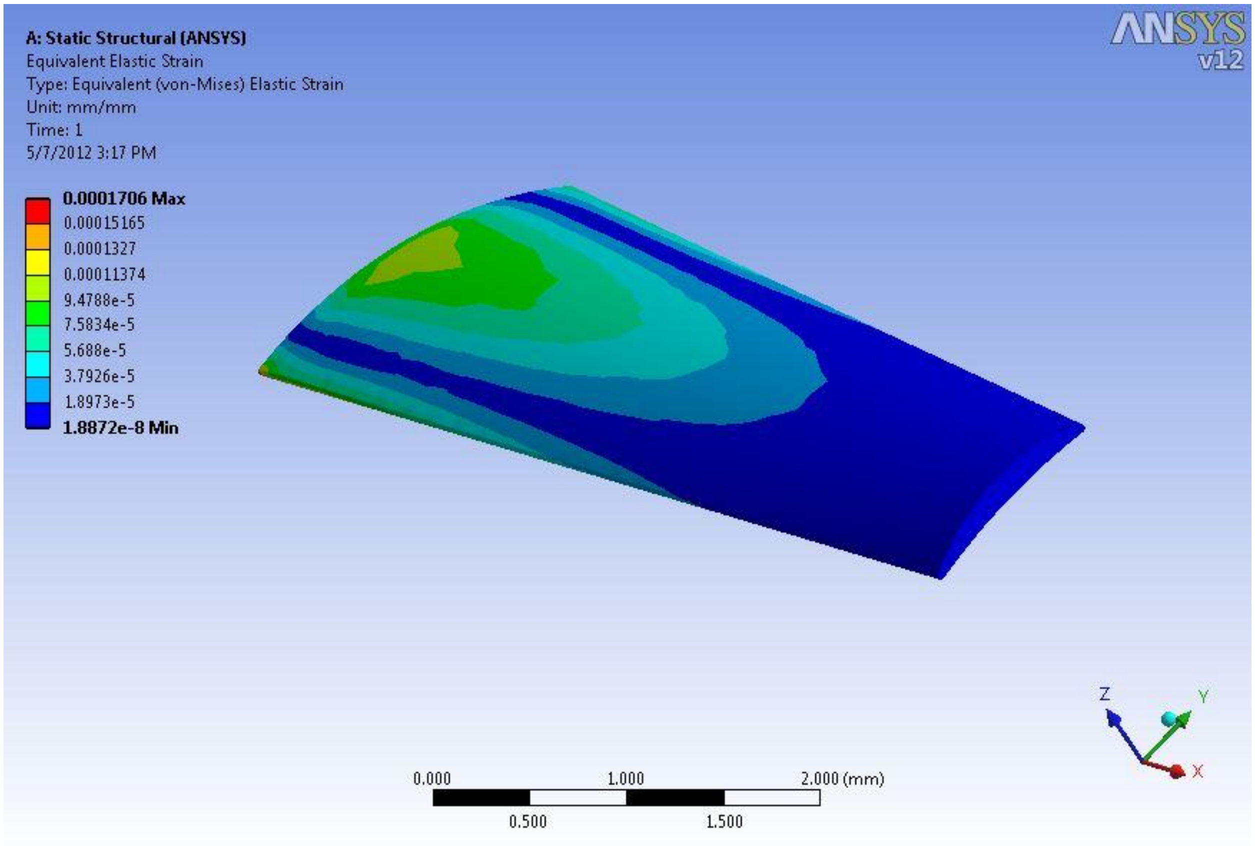

Fig.4.3 A screenshot of the von-Mises equivalent strain analysis of the rotor blade under load in ANSYS

The stress and strain at different parts of the blade are obtained in ANSYS and are presented in Fig.4.2 and Fig.4.3, respectively.

4.3 Speed of the rotor in hover condition

At hover condition, the lift force and the weight of the helicopter balance each other out. Hence.

Lift force on 2 rotor disks = Weight of helicopter body.

- ⇨ $2 \times 0.5 \times C_L \times \rho \times v_b^2 \times A = W_b$
- ⇨ $1.6 \times 1.29 \times v_b^2 \times 0.011304 = 0.19796$
- ⇨ $v_b = 2.912$ m/s = 7.73 rev/s
- ⇨ $\Omega_h = 463.82$ rpm.

This is the speed of the rotor at which the helicopter hovers and this is the speed at which the helicopter takes off because at this speed, the lift generated just equals the weight of the helicopter and as the speed increases from this value, the lift force keeps increasing and the weight remains the same.

5. CONCLUSIONS

5.1 Summary

In this work, an attempt is made to design and fabricate a coaxial micro helicopter. The dynamic forces are evaluated and static analysis is carried out in ANSYS. Even though there are no noticeable conclusions, the following is observed:

1. Speed of the rotor is obtained in section 2.11 as 473.6 rpm and at that speed of the rotor, the lift generated is found to be 0.206358 N in section 4.1.2. This lift force is found to be greater than the weight of the helicopter, which is found to be 0.19796 N in section 4.1.1. Thus, the lift force generated is calculated to be greater than the weight of the helicopter, which is the necessary condition for take-off. This result is confirmed in the fabricated model which takes off as expected.
2. Speed of the rotor in hover condition is found out be 463.82 rpm in section 4.3. This is the speed at take-off state of the helicopter. Thus, it is concluded that the speed of the rotor must lie between the limit values of 463.82 rpm and 473.6 rpm for the helicopter to be in flight. Any speed less than 463.82 rpm will result in the lift force to be less than the weight for which the helicopter will not take off or if in flight, will fall down.
3. The ANSYS analysis for von-Mises stress in Fig.4.2 shows that the hinged tip of the rotor blade experiences a stress in the limit from 18.958 MPa to 22.748 MPa. As this range of values is less than the tensile strength of polystyrene, which is 52 MPa, therefore no signs of fracture are observed and the analysis is safe. The free tip of the rotor blade experiences a very low von-Mises stress of 3.7945 MPa, which is acceptable.

4. The ANSYS analysis for von-Mises strain in Fig.4.3 shows that the hinged tip of the rotor blade experiences a strain in the limit from 0.00011374 to 0.0001327 and the free tip experiences minimal strain of 1.8872×10^{-8}.

5.2 Future scope of work

In the fabricated model there arose problems in the control of the yaw motion of the helicopter fuselage. Study regarding the control of the yaw motion can be attempted and used in the model.

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